STATISTICAL DETECTION AND CLASSIFICATION OF TRANSIENT SIGNALS IN LOW-BIT SAMPLING TIME-DOMAIN SIGNALS

GELU M NITA*, AARD KEIMPEMA**, ZSOLT PARAGI**

*NEW JERSEY INSTITUTE OF TECHNOLOGY

**JOINT INSTITUTE FOR VLBI ERIC

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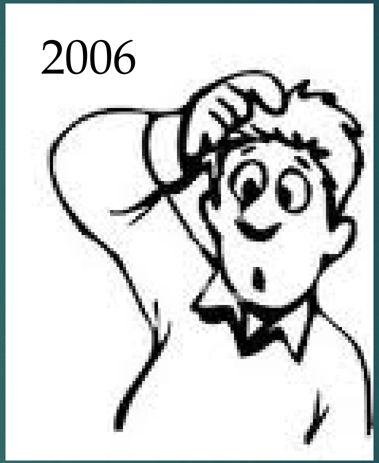
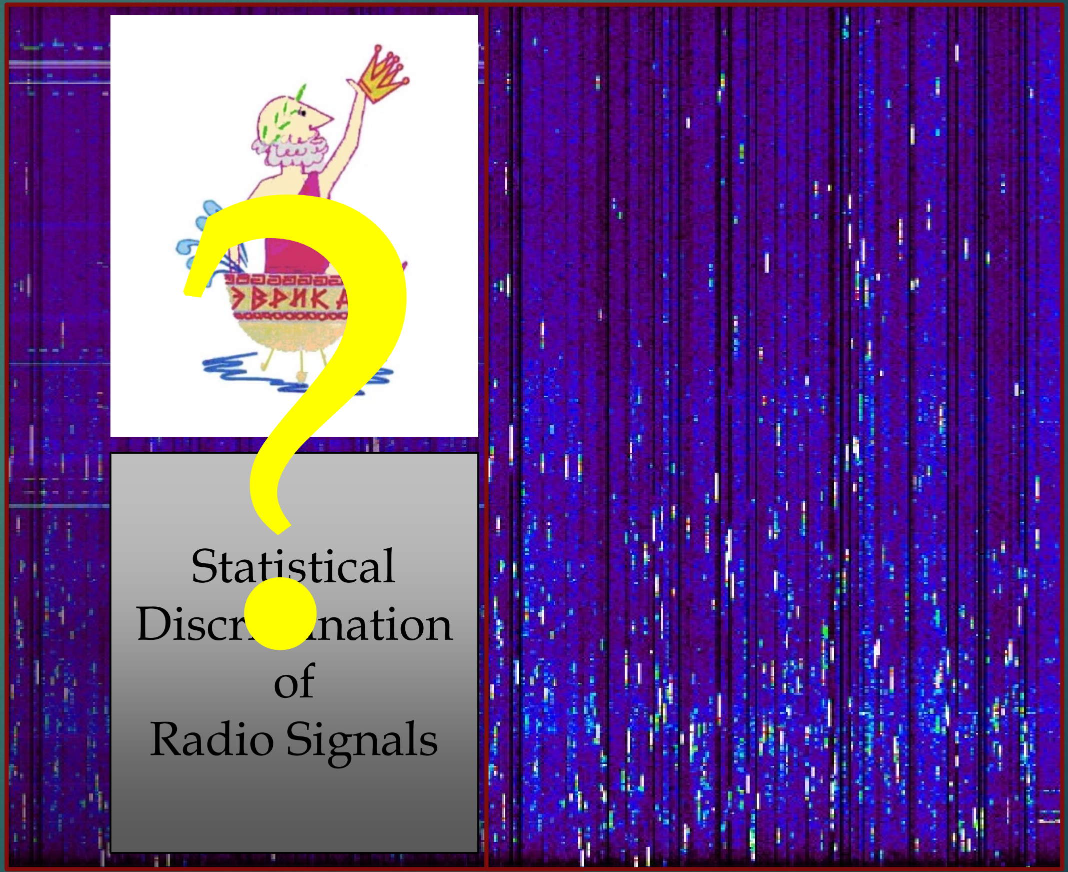
A well-known radio data analysis challenge



And its not so widely-known statistical solution…



Statistical
Discr[illegible]nation
of
Radio Signals

Radio Frequency Interference

Astrophysical Signal

The Generalized Spectral Kurtosis Estimator

Nita and Gary 2010, MNRAS 406 L60-L64

Theorem: Given that, for a particular signal, the set of its power estimates P_k obeys a gamma distribution characterized by the shape parameter ***d***, the infinite series of statistical moments $MS_2/{S_1}^2$, were $S_1 = \sum_{k=1}^{M} P_k$ and $S_2 = \sum_{k=1}^{M} {P_k}^2$ is given by

$$E\left[\left(\frac{MS_2}{S_1^2}\right)^n\right] = \frac{M^n\Gamma(Md)}{\Gamma(d)^M\,\Gamma(Md+2n)} \times \frac{\partial^n}{\partial t^n}\left[\sum_{r=0}^{n}\frac{1}{r!}\Gamma(2r+d)t^r\right]^M\Bigg|_{t=0}$$

The Generalized Spectral Kurtosis Estimator:

$$SK = \frac{Md+1}{M-1}\left(\frac{MS_2}{{S_1}^2} - 1\right)$$

Statistical properties of the SK estimator:

- Has an unbiased unity expectation $E[SK] = 1$, independent of the integrated power S_1
- The infinite series of statistical moments of its PDF are analytically defined only in terms of M and d

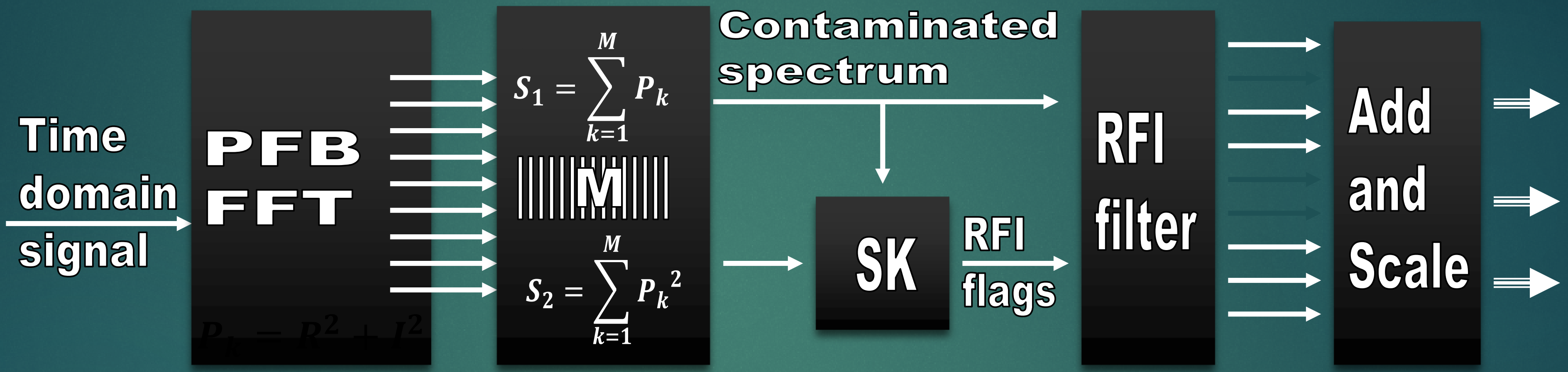
The SK estimator is well suited for detecting mixed signals not obeying the same gamma probability distribution: Detection thresholds of deviation from unity characterized by analytically defined probabilities of false alarm (PFA)

Practical cases well suited for SK analysis

- Raw power estimates based on time domain real signals
  - Gamma distribution of shape factor $d=0.5$ (Chi-Square distribution)
- Raw power estimates based on time or frequency domain complex signals
  - Gamma distribution of shape factor $d=1$ (Exponential distribution)
- Accumulations of N raw power estimates of shape factor δ
  - Gamma distribution of shape factor $d=N\delta$
- Power estimates based on quantized time domain signals or quantized frequency domain power estimates (Nita, Gary, and Hellbourg 2017, IEEE)
  - Gamma distribution having an instrument-dependent shape factor d

The Spectral Kurtosis Spectrometer

Nita et al. 2007 PASP, 119, 805
Gary, Liu & Nita 2010 PASP, 122, 560



The unbiased Spectral Kurtosis Estimator

$$SK \equiv \frac{M+1}{M-1}\left(\frac{MS_2}{S_1^2}-1\right)$$

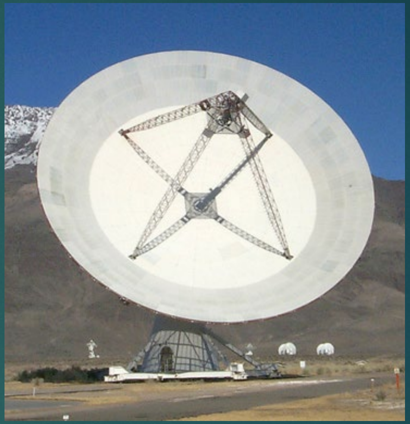
$$E\left(SK\right)=1$$

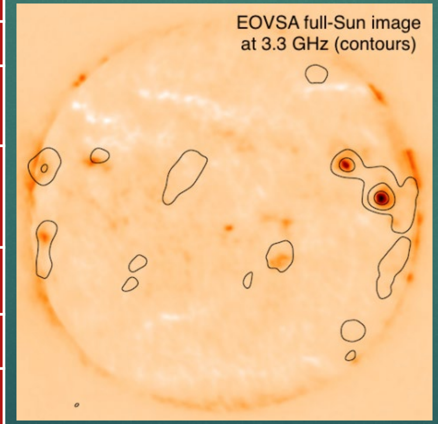
$$\sigma^2(SK) \approx \frac{4}{M}$$

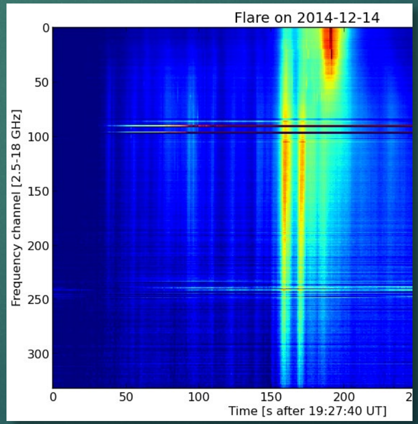
Expanded Owens Valley Solar Array

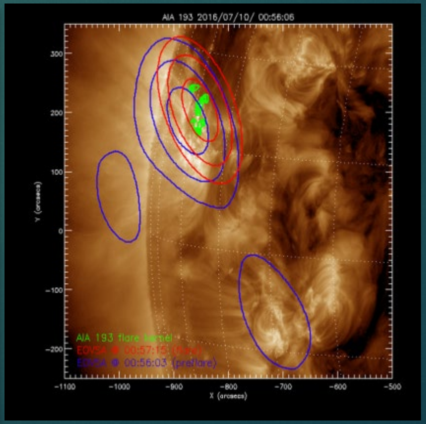
World-first frequency agile interferometer equipped with an hardware embedded SK real-time computation engine

Table 1: EOVSA Specifications	
Frequency range	2.5 – 18 GHz
Number of data channels/antenna	2 (dual polarization)
IF bandwidth	500 MHz single sideband
Frequency resolution	4096 spectral channels per 600 MHz band) 500 science channels variable ~1-40 MHz
Time resolution	Sample time: 20 ms Full Sweep: 1 s
Polarization	Full Stokes (IQUV)
Number correlator inputs per poln	16
Number and type of antennas	Thirteen 2.1-m Two 27-m equatorial (cal. only)
System Temperature	570 K (2 m); 35 K (27 m)
Baselines for imaging	78
Angular resolution	$56/n_{GHz} \times 51/n_{GHz}$ arcsec



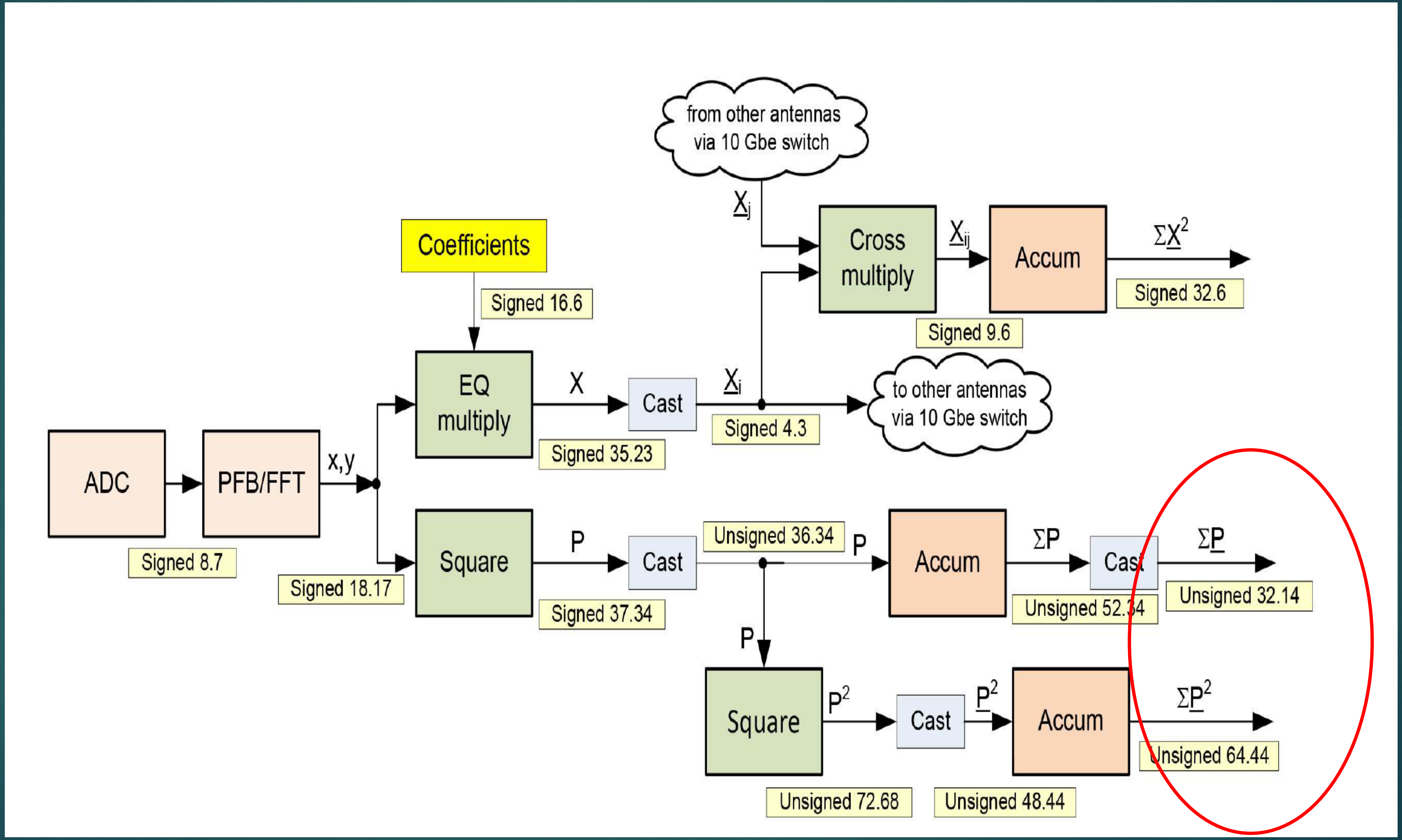




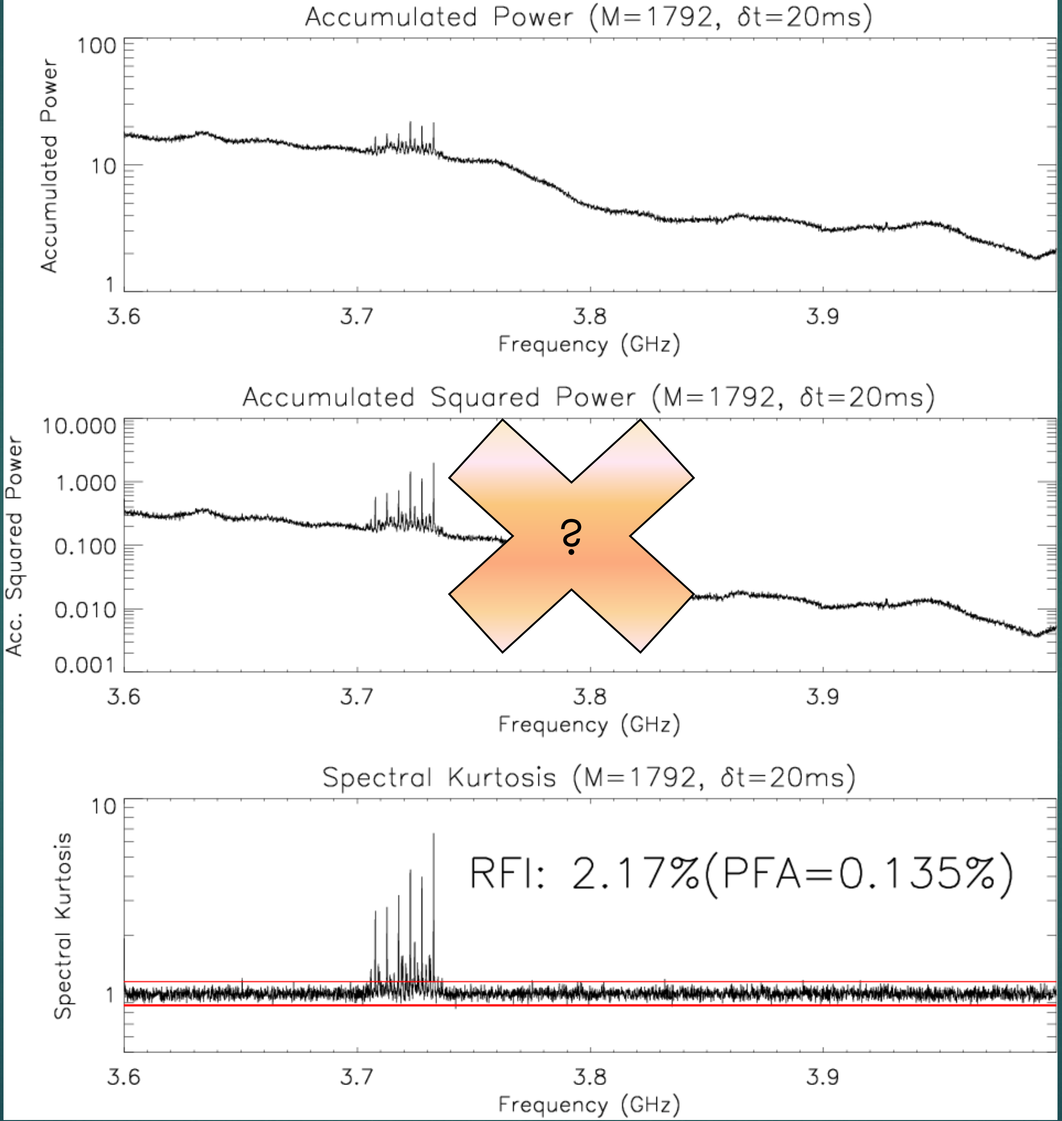


The EOVSA correlator outputs integrated power and squared power for all 15 antennas and R and L circular polarizations with 20ms-0.125MHz time-frequency resolution

EOVSA CORRELATOR
High bit resolution POWER AND SQUARED POWER outputs
Nita, Hickish, MacMahon, and Gary 2016, J. Astronomical Instrumentation 5(4)



EOVSA SK RFI EXCISION EXAMPLE

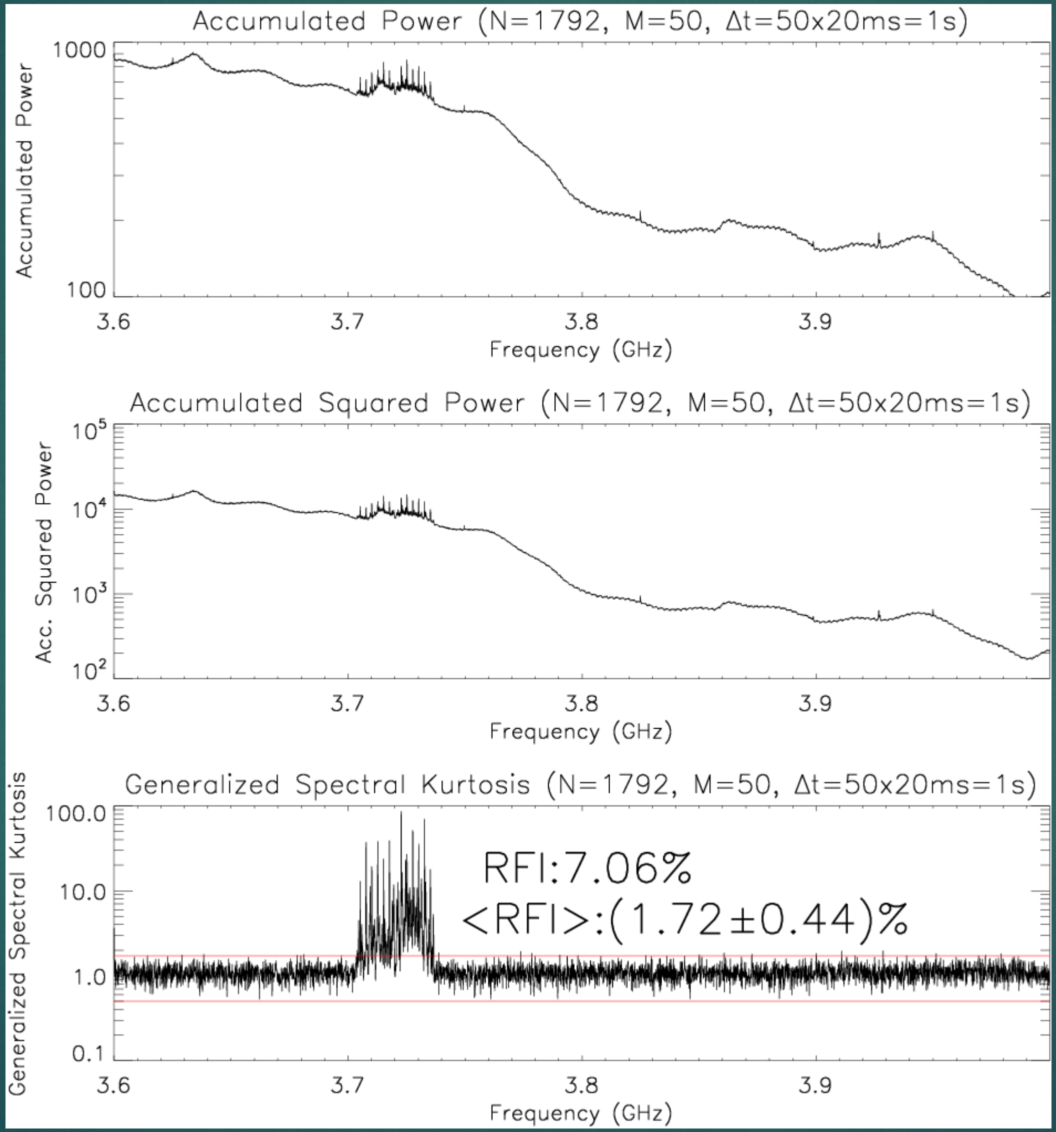


$$S_1 = \sum_{k=1}^{M} P_k$$

$$S_2 = \sum_{k=1}^{M} {P_k}^2$$

$$SK = \frac{M+1}{M-1}\left(\frac{MS_2}{{S_1}^2} - 1\right)$$

EOVSA Generalized SK Analysis



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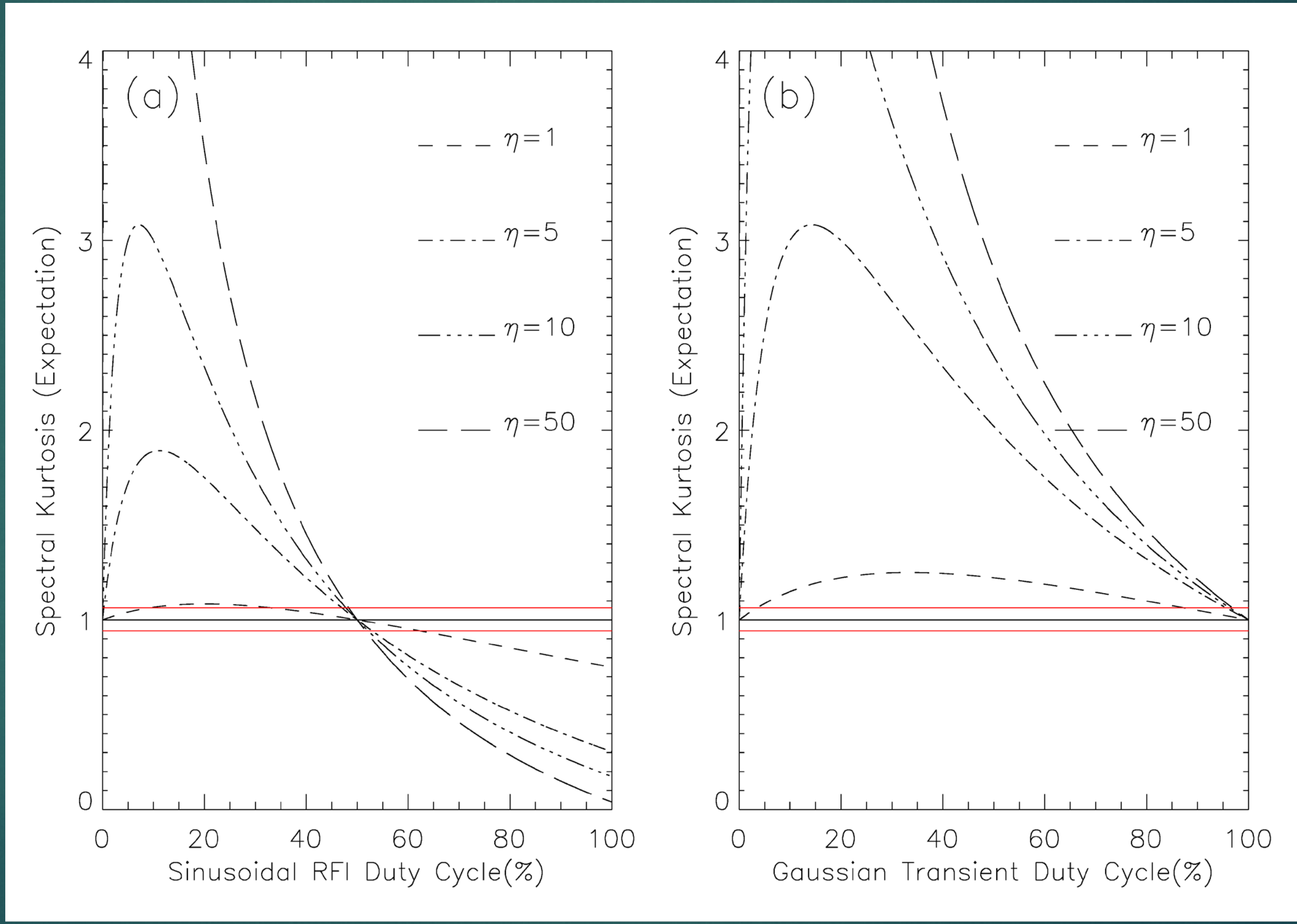
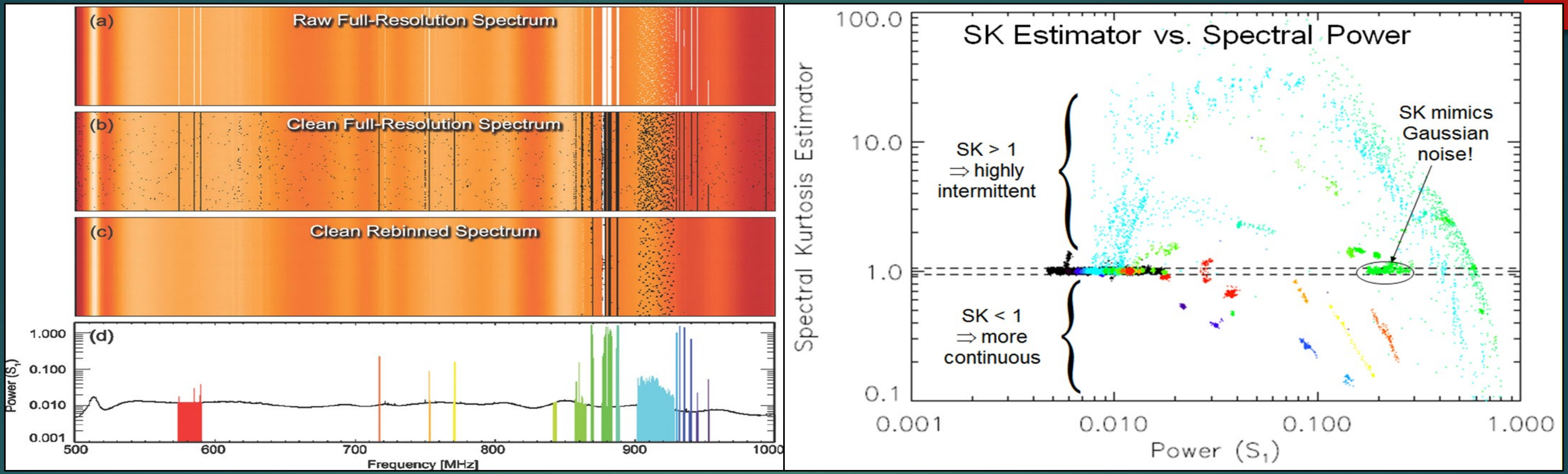
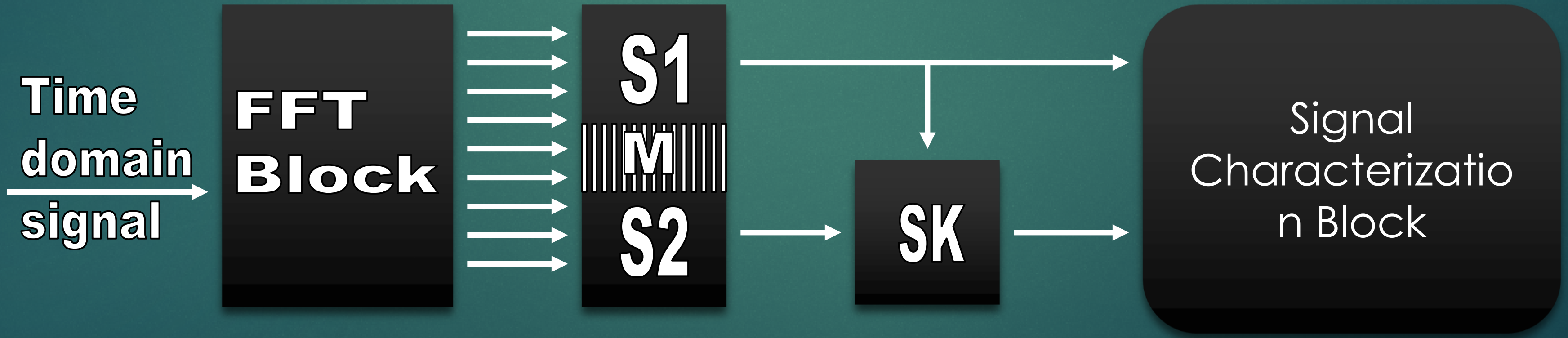
SK Dependence on the Integration–Relative Duty-Cycle RFI and Gaussian Transient Signals

(Nita et al. 2007, PASP, 119; Nita 2016, MNRAS, 458)

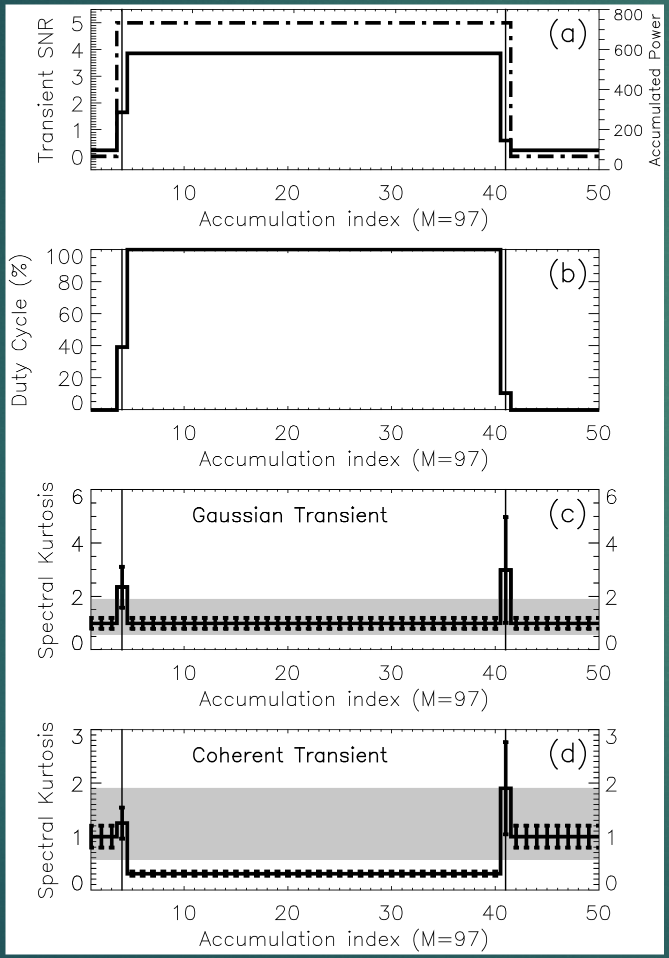


SPECTRAL KURTOSIS: A POWERFUL SIGNAL CLASIFICATION TOOL

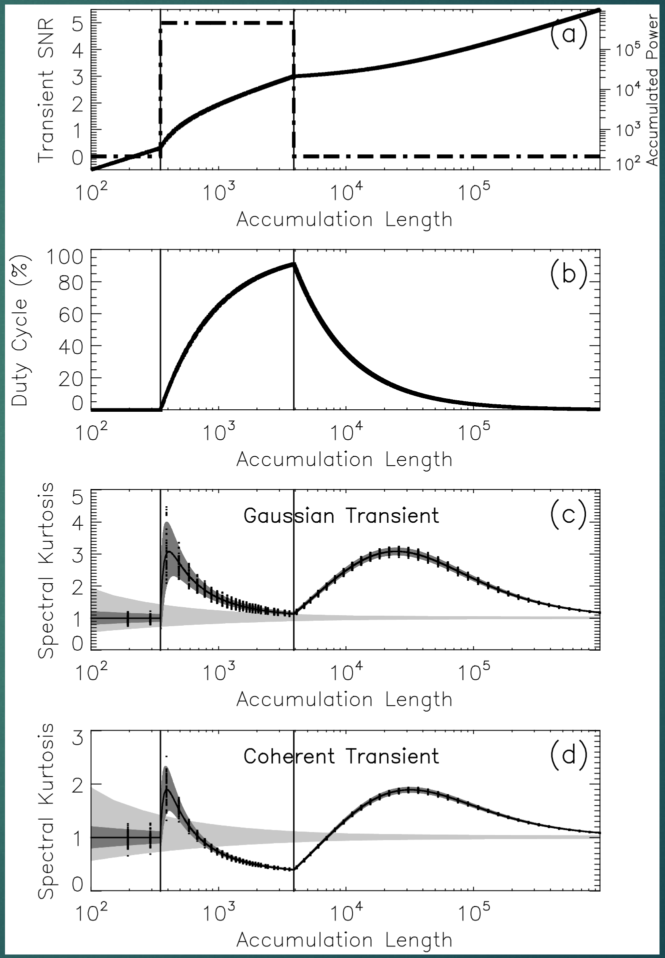




Multiscale SK Analysis : Real-Time Detection and Discrimination Transients (Nita 2016, MNRAS, 458)



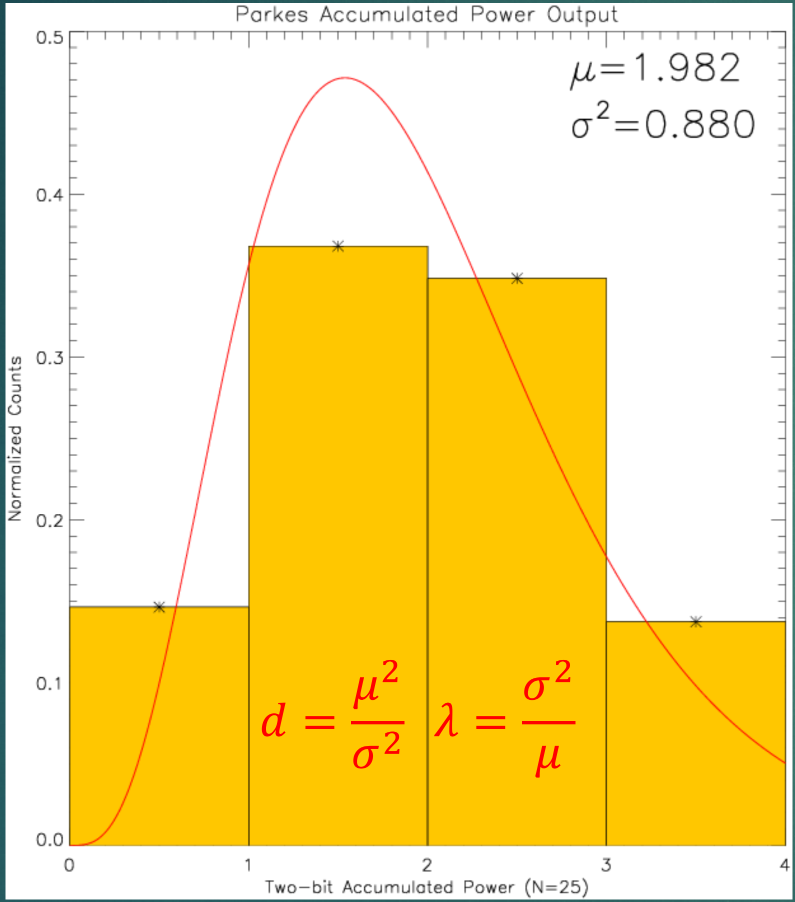
Monoscale SK Analysis



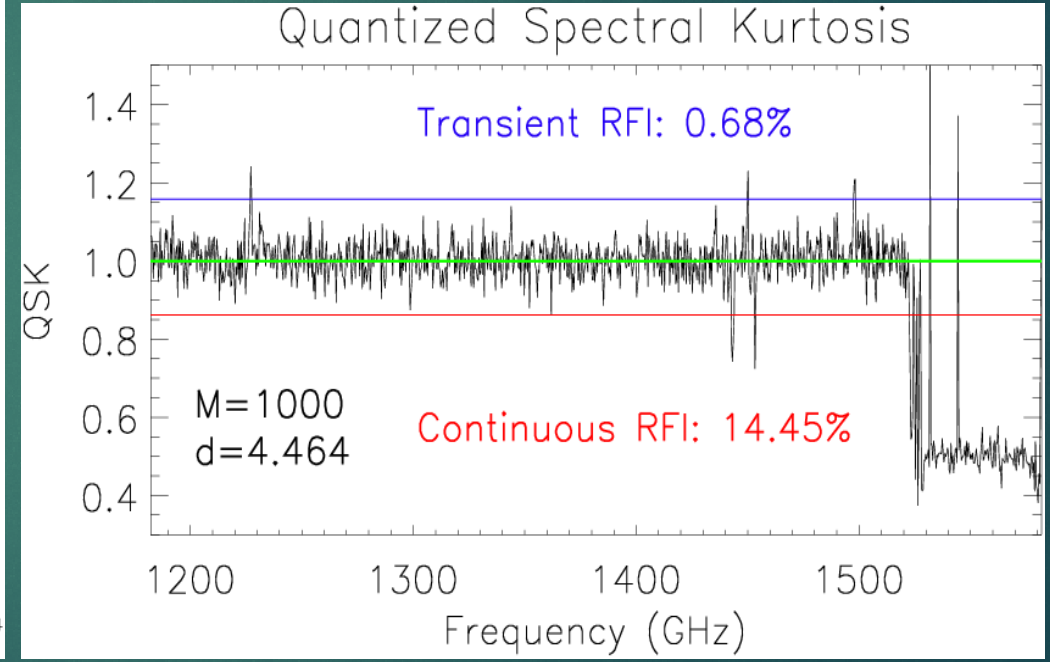
Multiscale SK Analysis

Spectral Kurtosis Statistics of Quantized Signals

Nita, Gary and Hellbourg 2016, IEEE RFI Workshop

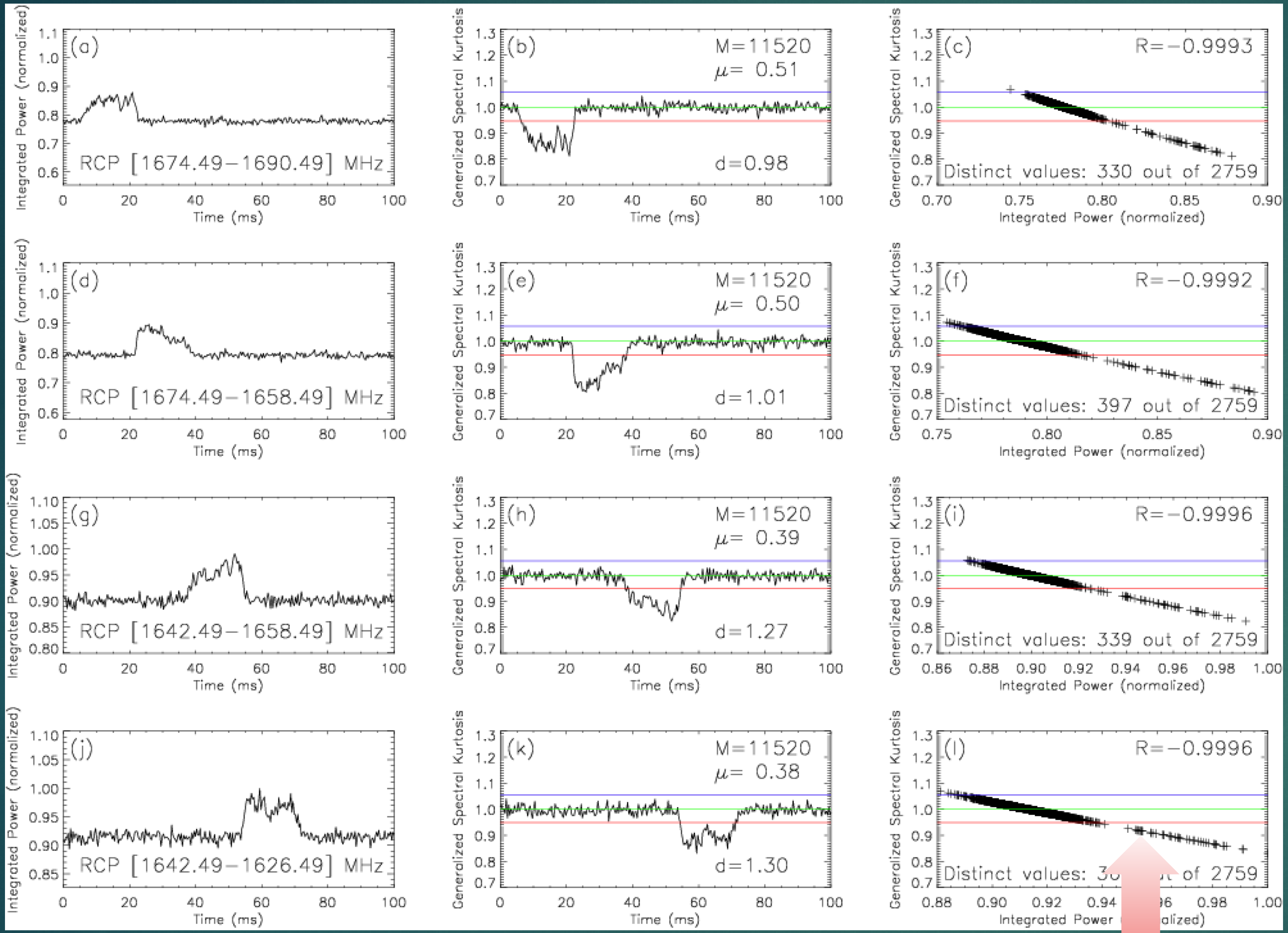


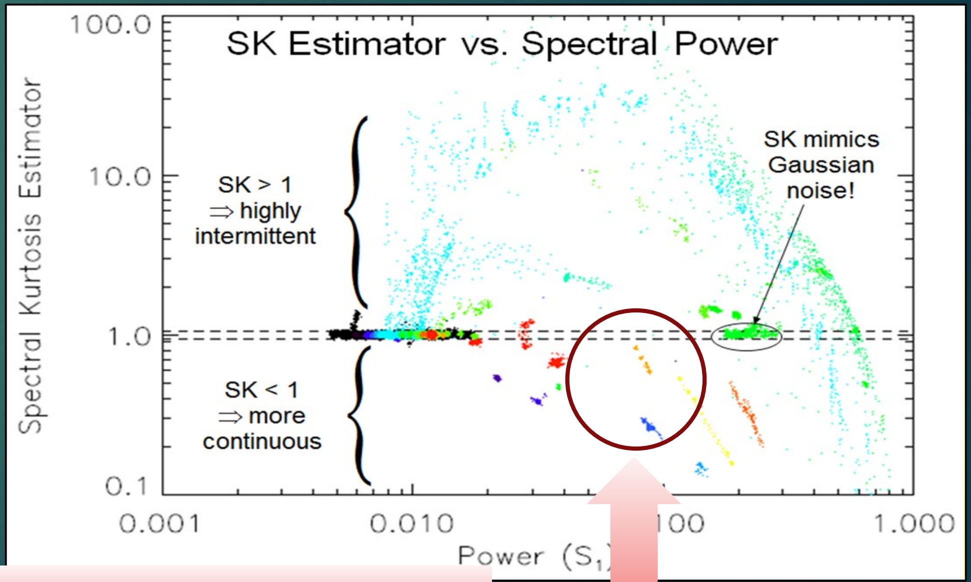
$$SK = \frac{Md+1}{M-1}\left(\frac{MS_2}{{S_1}^2} - 1\right)$$



The distribution of the Parkes Telescope quantized accumulated power output corresponding to a Gaussian time domain signal can be approximated by a Gamma distribution of shape parameter d<N, to which the Generalized Spectral Kurtosis theory may be applied.

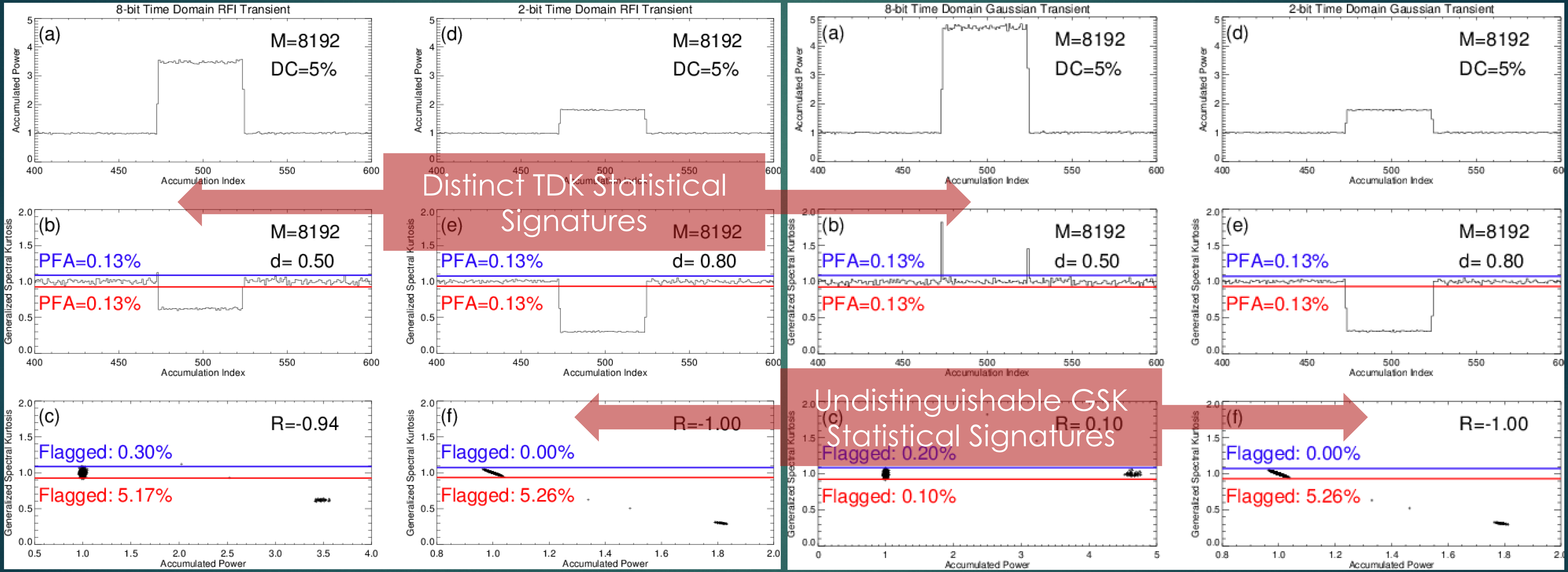
Time Domain GSK analysis of the VLBI 2-bit sampling RCP voltage data containg the FRB 121102 signal





RFI-like statistical signature of the FRB 121102 2-bit signal

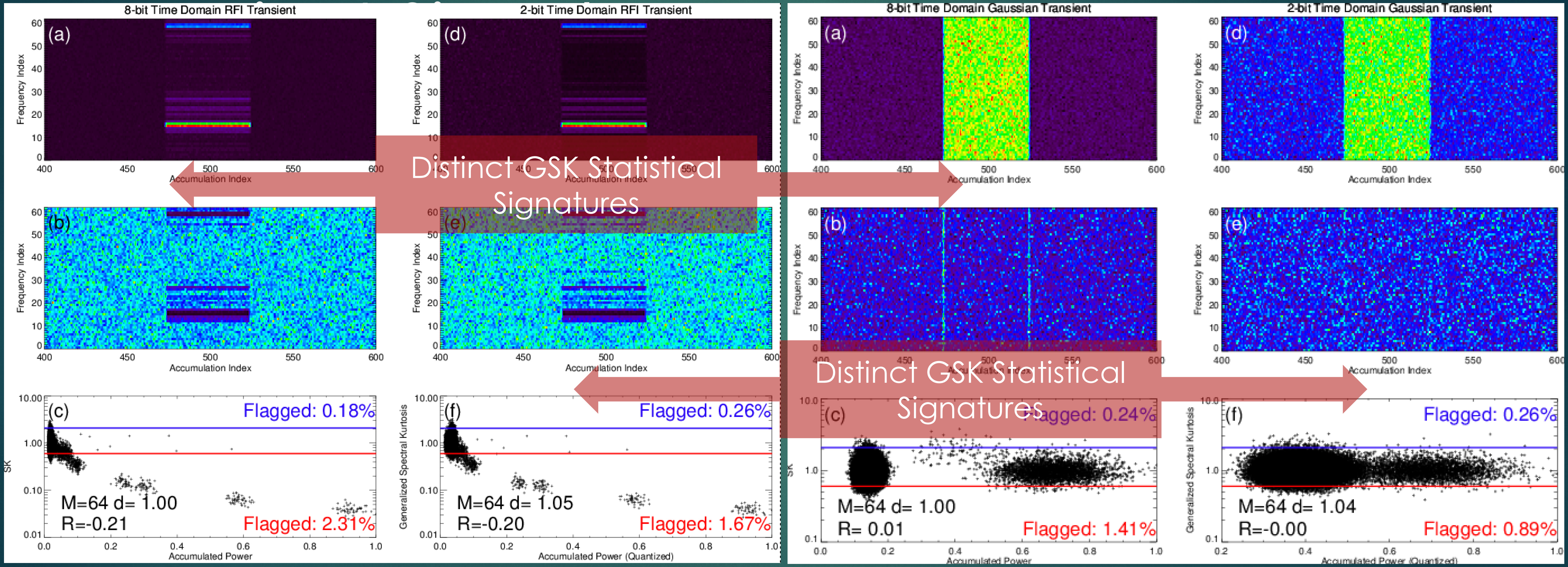
8-bit vs 2-bit Time-Domain GSK Analysis of RFI and Gaussian Signals



RFI Transient Signal

Gaussian Transient Signal

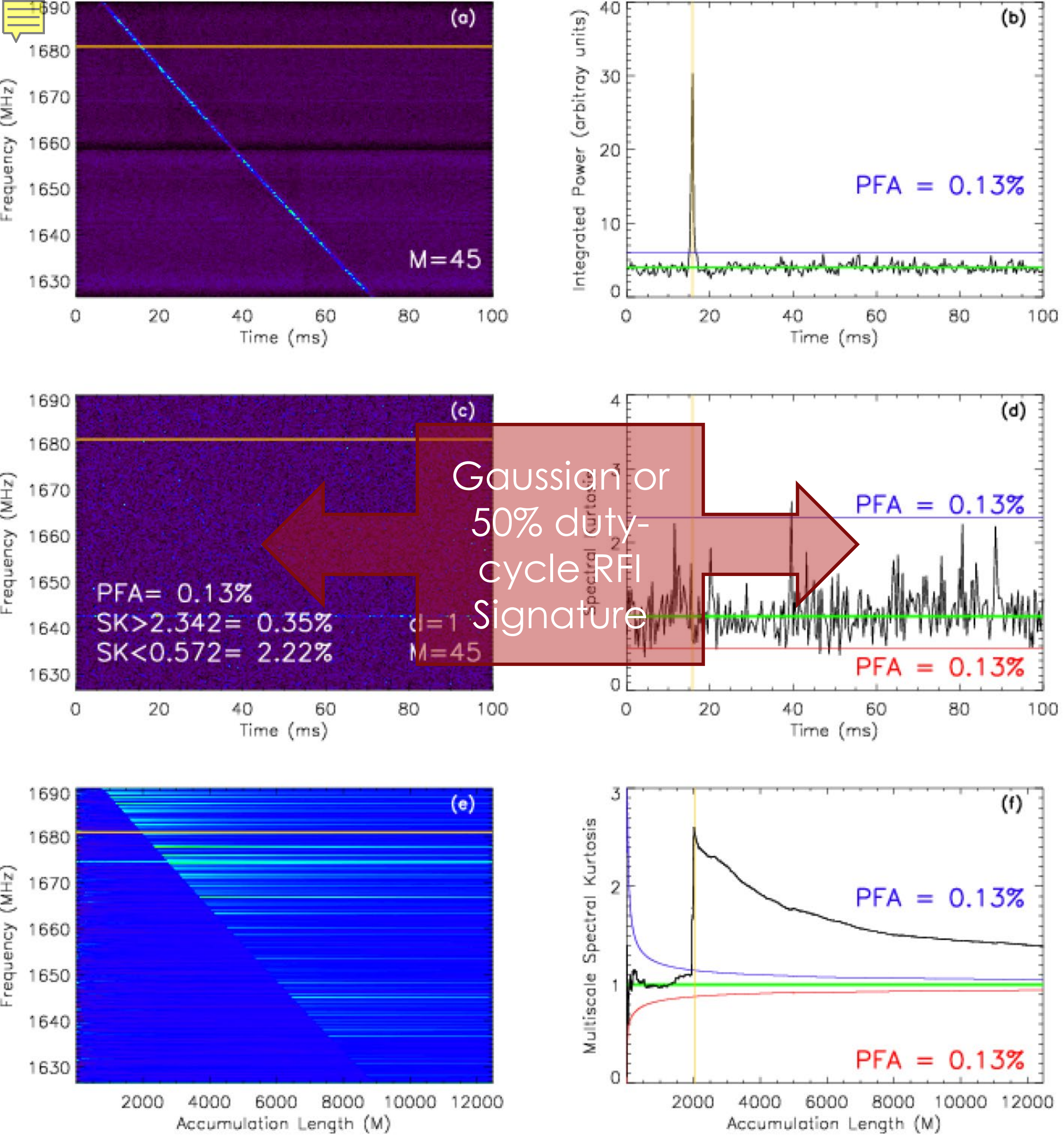
8-bit vs 2-bit Spectral-Domain GSK Analysis of RFI and Gaussian Signals



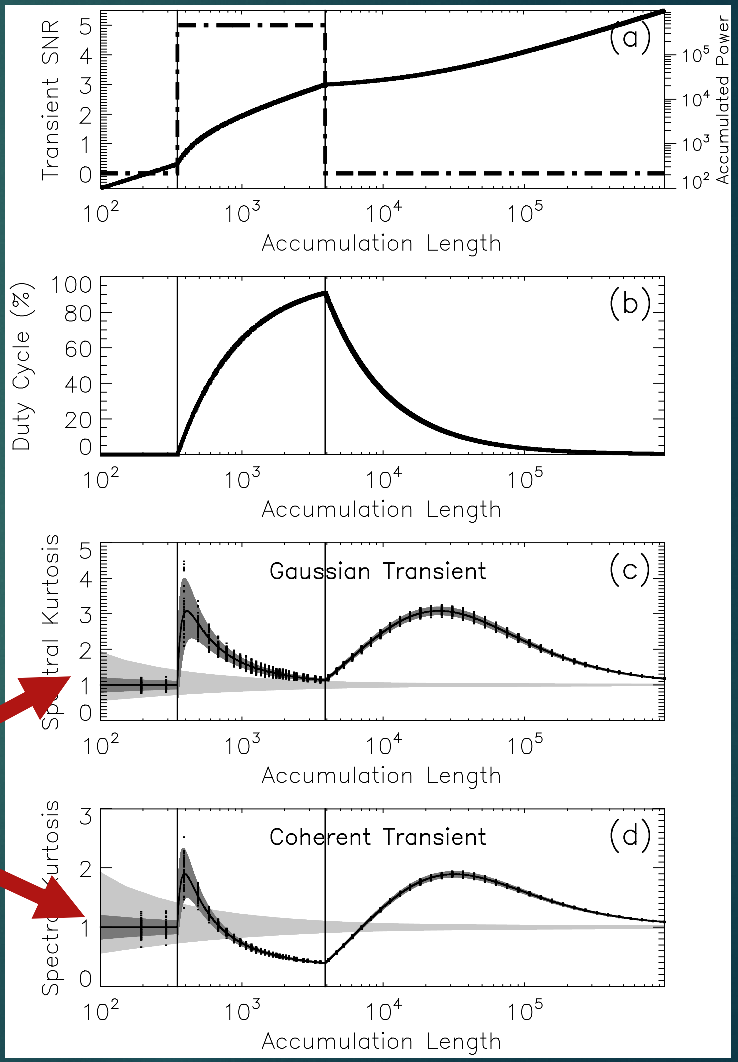
RFI Transient Signal

Gaussian Transient Signal

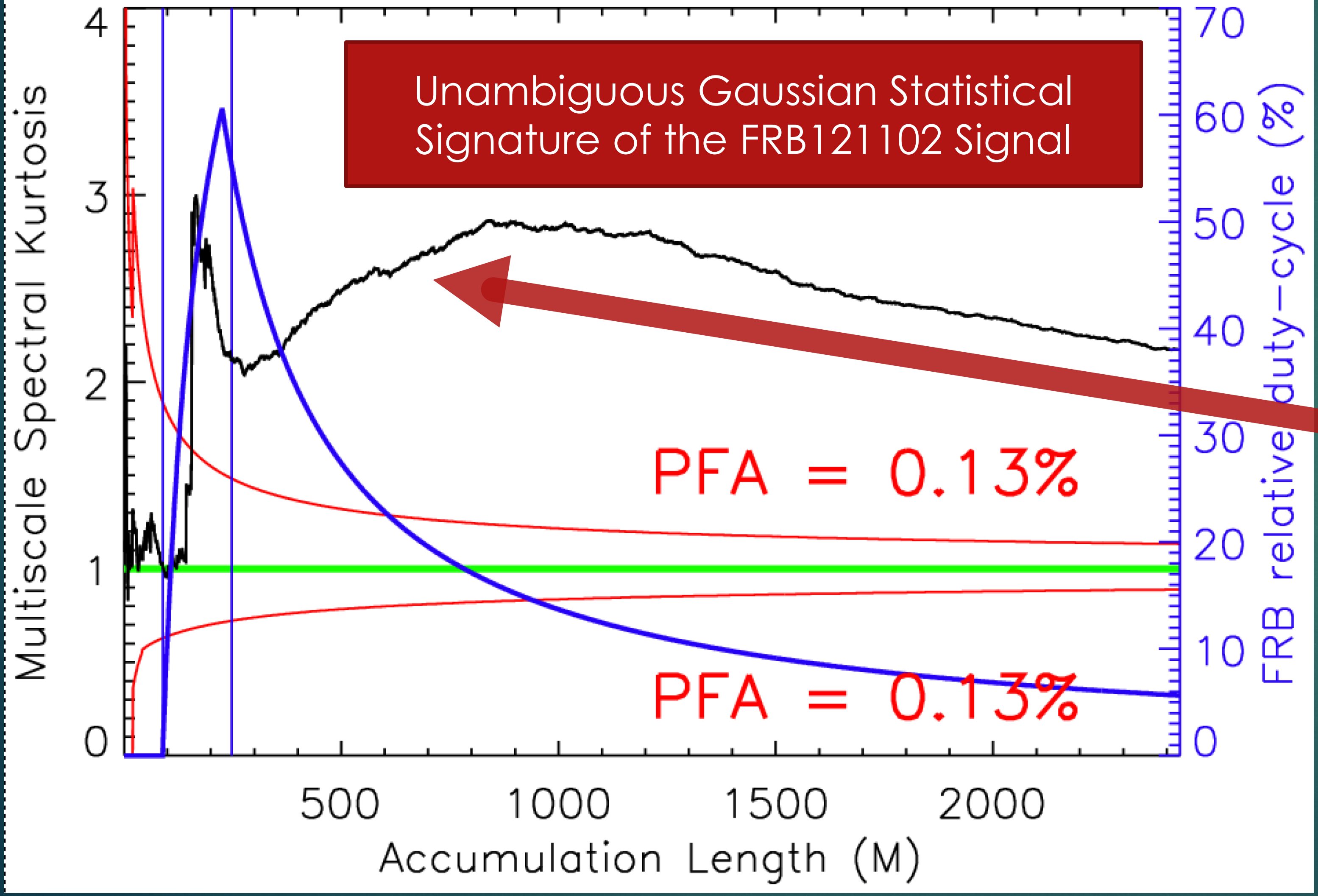
SK and Multi-scale SK Analysis

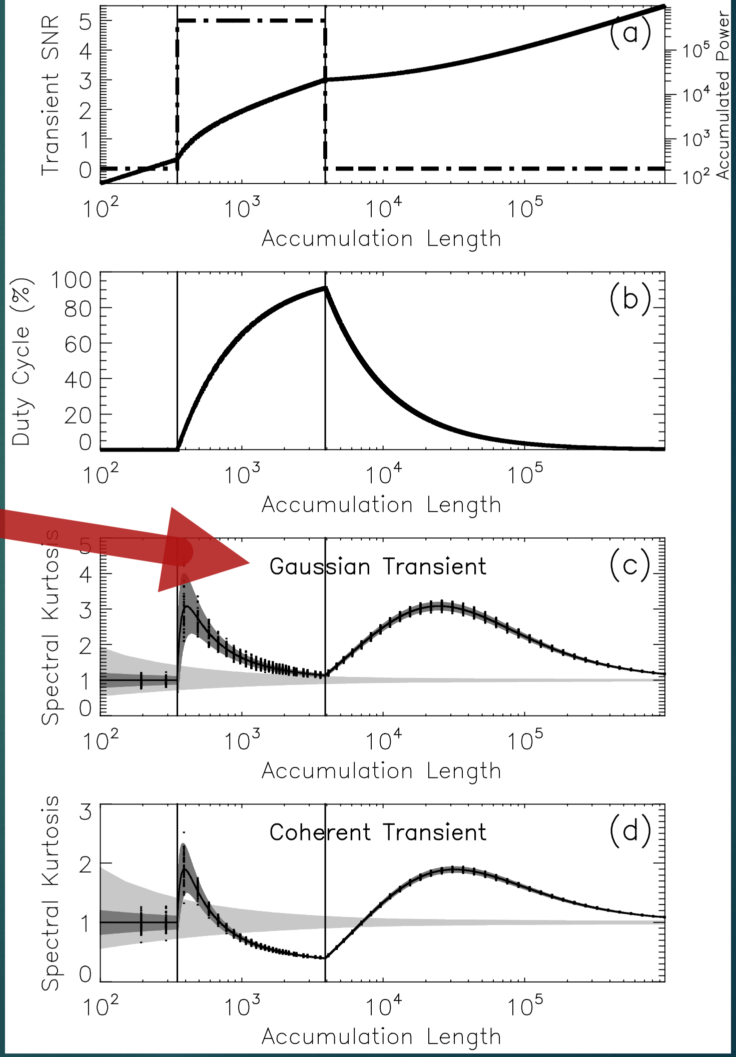


Gaussian or 50% duty-cycle RFI Signature



Multi-scale SK Analysis using an adaptive starting point of integration





Conclusions

- Time domain Kurtosis analysis of the 2-bit quantized VLBI signals can detect both RFI and natural astronomical transients but is not capable of distinguish them. Therefore, astronomical transients may be mistakenly flagged as RFI.
- Spectral Kurtosis analysis of the 32-bit FFT-transformed 2-bit time domain quantized VLBI signals can detect RFI while remaining blind to the presence of Gaussian transients (but may still detect sharp edges of such gaussian signals). Therefore it is generally safe to employ spectral domain SK analysis for the purpose automatic RFI excission.
- Multi-scale SK analysis of the 32-bit FFT-transformed 2-bit time domain quantized VLBI signals can detect both RFI and Gaussian transient signals and discriminate them based on their statistical signature. Therefore it is generally safe to employ spectral domain SK analysis for the purposeof detecting and discriminating RFI and natural transients.
- **Using multiscale SK analysis we unambiguously established, for the first time, the Gaussian nature of an FRB 121102 signal detected by VLBI**